PUBLICATIONS

OF THE

Astronomical Society of the Pacific.

VOL. XVIII. SAN FRANCISCO, CALIFORNIA, DECEMBER 10, 1906. NO. 111.

A REVIEW OF CERTAIN RESEARCHES ON RADIO-ACTIVITY THAT HAVE A BEARING UPON ASTRONOMICAL QUESTIONS.

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Since the discovery of the penetrating property of the X rays by Professor RÖNTGEN in 1895 the progress of certain branches of physical science has been so rapid that one not actually engaged in the work of investigation along these particular lines can scarcely keep pace with the new theories and discoveries. The most striking advances are a result of the study of radio-activity; the series of facts brought to light by this study being of so extraordinary a character as almost to bewilder the student. Just how much of a revolution in physical theory they will effect cannot now be estimated, but the prospect is such that no person interested in any branch of physical science can afford to be uninformed with regard to these discoveries. Their special interest to students of astronomy lies in their bearing upon theories of the constitution of matter and the relation between matter and electrical energy. The light which the study of the phenomena of radio-activity is throwing upon these questions must influence very materially theories of cosmological processes. It being obviously impossible to give anything like a complete account of this subject within the limits of such a paper, only those points are noticed that have a more or less direct bearing upon astronomical problems.

For the information contained in the following pages I am chiefly indebted to the two editions of Professor RUTHERFORD'S "Radio-activity," though other sources have been made use of, some of which are indicated by exact references.

Radio-activity is a property possessed by certain substances of emitting a so-called radiation which affects a photographic plate, and is detectable in other ways. The only substances which have so far been found to possess the property of radio-activity to any considerable extent are uranium, thorium, actinium, and radium, and certain "disintegration products" of these substances. There is, however, some experimental evidence in favor of the view that many substances are more or less radio-active.

Radium is the most active of the four substances mentioned above. If an unexposed photographic plate, protected from light by inclosure in a box, be left for a short time in the neighborhood of a small amount of radium and then removed and developed, it is found to be fogged.

Certain substances show fluorescence when brought into the presence of radium. I have seen an observer locate a small amount of radium which was behind a closed door by moving a screen of fluorescing substance about until it glowed, when opposite the radium. Electrically charged bodies in air or in any other gas are rapidly discharged if there is a small quantity of radium in the neighborhood. Exposure of the human skin to the radiation produces irritation, and, where the exposure is excessive, severe inflammation which is very slow in healing. Radium also has the property of warming itself and the receptacle which contains it above the temperature of the surrounding atmosphere. The other three substances mentioned as possessing radio-active properties are less active than radium, but they undoubtedly possess all of these properties in a less marked degree.

The resemblance of these effects to the effects produced by the X rays at once suggests the theory that they are due to a radiation from the active substances similar in character to the X rays. It will be remembered that the latter will penetrate substances opaque to ordinary light, fog a photographic plate, discharge electrically charged bodies, produce fluorescence in certain salts, and cause irritation of the human cuticle.

A remarkable series of experiments performed in the Cavendish Laboratory by Professor J. J. THOMSON and his students led to the theory regarding the origin and nature of the X rays that is at present generally accepted. According to it,

the cathode rays consist of a stream of "electrons," each having a mass of about one thousandth of the mass of the hydrogen atom and carrying a certain definite charge of electricity, known as the "ionic charge," being the charge carried by an ion of unit valency in electrolysis. The X rays are thought to be ether-pulses set in motion when the electrons meet with any obstacle which retards them in their flight, as, for example, the glass walls of the vacuum-tube.

Investigation of the radiations from radium and the other active substances has brought out the fact that three different kinds of "radiations" are emitted. They are known as the α, β, and γ rays, respectively. The α rays consist of a stream of particles having a mass of the order of magnitude of the hydrogen atom, and carrying a positive charge when observed in their flight through a gas. Recent observation indicates that these α particles are without an electric charge when ejected from the active substance, but acquire their positive charge upon collision with the atoms or molecules of the gas through which they fly.[1]

The β rays consist of a stream of negatively charged electrons,—that is, particles whose mass is about a thousandth of the mass of the hydrogen atom.

The γ rays are thought to be ether-pulses similar to the X rays, but differing from them in a certain quality of intensity. When a Crookes tube in which the vacuum is of an exceedingly high order is used to produce X rays, exceptionally penetrating rays, called "hard" rays, are produced. The γ rays bear a closer resemblance to the hard X rays than to the ordinary, or soft, X rays, and it seems probable that the difference between the γ rays and the X rays is only in this quality of "hardness."

A gram of radium in radio-active equilibrium emits about 2.5×10^{11} α particles per second with velocities varying between ten and thirteen thousand miles per second.[2] The heat equivalent of the kinetic energy of this stream of particles is about 100 gram calories per hour. This is roughly the amount of heat necessary to melt one gram of ice. A gram of radium generates sufficient heat by the bombardment of its α particles to melt its own weight of ice each hour.

[1] *Nature,* August 2, 1906, p. 316. [2] *Phil. Mag.,* October, 1906, p. 369.

The number of β particles emitted by a gram of radium per second is estimated to be 7×10^{10}, and they are emitted at velocities of from 35,000 to 190,000 miles per second. Their mass is so small that the kinetic energy of their flight is small as compared with that of the stream of α particles.

The γ rays are thought to arise from the acceleration of the β particle somewhat as the X rays are produced by the cathode particle as stated above. They are supposed to travel with the velocity of light.

It seems to be quite certainly established that the energy developed by radium, due to the bombardment of the α particles, is not derived from any external source, but is contained in the radium atoms. Accompanying this discharge of energy there is supposed to occur a disintegration of the radium atom. This disintegration occurs at such a rate that half of any given quantity of radium would disintegrate in 2,600 years,[1] a half of the remainder in the next 2,600 years, and so on. Thus, if a gram of pure radium were put into a closed tube and examined at the end of a period of 5,200 years, it would be found that the tube contained one fourth of a gram of radium and such of the products of the disintegration of the other three quarters of a gram as had not escaped through the walls of the tube. All this time the radium in the tube would be radiating heat sufficient to melt its own weight of ice each hour.

It is clear from the preceding statements that the atoms of the radio-active substances must be regarded as storehouses of comparatively enormous amounts of energy. About two pounds of radium would give off in the course of its disintegration sufficient energy to drive one of our largest ocean liners across the Atlantic at record-breaking speed.

The analysis of the disintegration products of the radio-active elements is one of the triumphs of modern research. It should be remarked that the claim that an actual disintegration of a *chemical element* takes place has been called in question by Lord KELVIN, and has been the subject of an animated controversy among English physicists and chemists.[2] The result of the discussion was simply to bring out the fact that we may either regard the radio-active substances as

[1] RUTHERFORD, *Phil. Mag.*, October, 1906, p. 367.

[2] See letter by SODDY, *Nature*, September 20, 1906, p. 516.

unstable chemically complex substances or as unstable elements. It is the propriety of calling these substances elements and not the fact of disintegration that has been called in question.

The disintegration theory offers very simple and direct explanations of a multitude of observed phenomena, and I shall proceed to give an account of the observed facts of the "disintegration" of the radio-active substances as interpreted by the theory advanced by RUTHERFORD and SODDY.

The four radio-active substances—uranium, thorium, actinium, and radium—disintegrate so slowly (radium being by far the most rapid of the four) that it is difficult, and in most cases impossible, to collect a sufficiently large amount of the disintegration products to make an analysis of them by chemical or spectroscopic methods. The property by which their presence is detected is their radio-activity (for most of the disintegration products are themselves radio-active). It will be remembered that one of the properties of radio-active substances is the ability to discharge an electrified body in its neighborhood. If a current of air is drawn through a tube containing radium and passed into a charged electroscope, the electroscope is quickly discharged. This suggests the theory that radium gives off a gaseous disintegration product, itself radio-active, which is carried with the air-current into the electroscope. Other tests confirm this theory. Fortunately enough of this "radium emanation" can be collected to make a chemical examination possible. It is found to be an inert gas of the argon group and of high atomic weight.

The walls of a vessel in which the radium emanation is allowed to disintegrate are found to become radio-active, and it has been ascertained that the product of disintegration of the emanation is a solid, called "radium A," which condenses on the walls of the vessel containing the emanation, and that this radium A disintegrates, forming another substance—radium B. The four substances—radium, the emanation, radium A, and radium B—possess distinct physical and chemical properties. Three are solid, the fourth a gas. Radium A and B can be separated by certain chemical processes, but cannot be collected in sufficient quantities for chemical examination. Three other substances, each having its distinctive

chemical properties, are quite certainly "disintegration products" of radium. These are designated as radium D, E, and F, respectively.

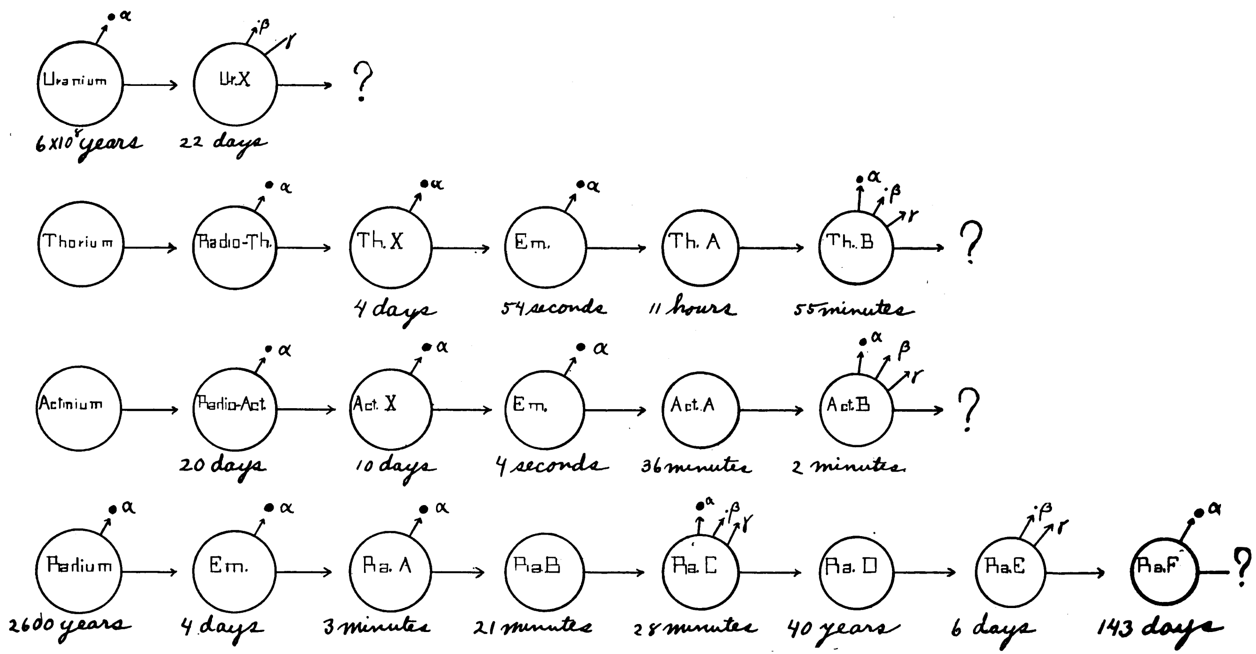
Most of the progress in the analysis of the disintegration products is due to experiments suggested by the hypothesis that each active substance disintegrates as a function of the time according to a simple law similar to the one stated above for radium. There is a certain period of time (2,600 years in the case of radium) during which the activity of a given amount of the active substance decays to half value. Where the period of decay to half value amounts to only a few hours or minutes, as it does in the case of most of the disintegration products, it is possible, by making observations on the activity of a product at intervals during its decay, and plotting the activity against the time, to tell whether the active substance under examination is simple or not. In this way it was discovered that the active matter deposited after the decay of the radium emanation was not a simple substance, but a combination of two substances, which it was afterwards found possible to separate by chemical methods.

According to the foregoing, each of the disintegration products is characterized by its period of decay. They are further characterized by the type of radiation given off. Some emit α rays only, some β and γ rays only (these two kinds of rays never occur separately), some emit α, β, and γ rays, and others seem to be rayless changes. A table is given on the opposite page exhibiting the results of the analysis of the disintegration of the four substances previously mentioned. It is a copy of the one given in the second edition of RUTHERFORD'S "Radio-activity" with the few changes necessary to bring it up to the date of this writing.[1]

It is not possible to measure directly the mass of the α particle but the ratio $(\frac{e}{m})$ of the charge to the mass of the particle can be measured. The value of $\frac{e}{m}$ seems to be the same for α particles from all of the radio-active substances and their disintegration products.[2] If it is assumed that the charge e is the ionic charge, the mass of the α particle is about twice

[1] HAHN, *Phil. Mag.*, July, 1906, pp. 92, 93; LEVIN, *Phil. Mag.*, September, 1906, p. 188; RUTHERFORD, *Phil. Mag.*, October, 1906, p. 367.

[2] RUTHERFORD, Phil. Mag., October, 1906, p. 364.



Uranium
Ur.X
?
6x10^8 years
22 days
Thorium
Radio-Th.
Th.X
Em.
Th. A
Th. B
?
4 days
54 seconds
11 hours
55 minutes
Actinium
Radio-Act.
Act. X
Em.
Act. A
Act. B
?
20 days
10 days
4 seconds
36 minutes
2 minutes
Radium
Em.
Ra. A
Ra. B
Ra. C
Ra. D
Ra. E
Ra. F
?
2600 years
4 days
3 minutes
21 minutes
28 minutes
40 years
6 days
143 days
α
β
γ

that of the hydrogen atom. If it be assumed that the charge is twice the ionic charge, the mass of the α particle must be regarded as four times that of the hydrogen atom. This is the mass of the helium atom, and the presence of helium in minerals containing the radio-active substances, together with evidence of the growth of helium in vessels containing radium emanation, suggests the hypothesis that the α particle is an atom of helium. There is considerable evidence, derived from a study of the relative amounts of uranium and radium found in old minerals, that radium is a disintegration product of uranium, with probably other products intervening.[1]

A remarkable characteristic of these radio-active disintegrations is their almost total independence of the physical or chemical state of the disintegrating substance. The decay proceeds at the same rate at the temperature of liquid air as it does at the temperature of the Bunsen flame. Only one exception to this rule has been discovered. The rate of decay of radium C is somewhat accelerated for temperatures between 630° and 1300° centigrade. Chemical compounds of an active substance are active and the degree of activity indicates that the active substance is suffering transformation, as if it were in an uncombined state. The various devices by which ordinary chemical reactions are accelerated or retarded fail to produce any effect upon the rate of decay of a radio-active substance, except in the above-mentioned case of radium C.

It has been known for some years that the air above the land contains a radio-active substance. No observations for radio-activity seem to have been made on air collected in midocean. This radio-activity of the air is due to the presence in it of the emanations of radium and thorium. Air drawn from the soil is always more or less radio-active, and radium is widely distributed through the Earth's crust.

The question has been raised whether all matter is not radio-active to a greater or less extent. Experiments have been made which seem to favor this view, but it is impossible to make sure that the observed radio-activity is not due to the presence in the substance under investigation of minute quantities of one of the four substances whose radio-activity is recognized, or

[1] For evidence of the production of radium from actinium, see letter by BOLTWOOD, *Nature*, November 15, 1906, p. 54.

of their decomposition products. It is a well-known fact that many substances emit negatively charged particles when illuminated with ultra-violet light, and metallic sodium does so without this stimulus. However, this phenomenon differs essentially from that of radio-activity, particularly in the dependence of the activity upon the excitation of the ultra-violet light.

The "rayless" changes which some of the disintegration products of the radio-active elements are known to undergo (e. g. Th. A to Th. B) suggest the suspicion that ordinary matter may be disintegrating in such a way that the process escapes observation. The rayless changes of the disintegration products are detectable only because they are transition stages between two active products. Ordinary matter may be undergoing a "rayless" transformation which escapes observation. The products of such decay would be expected to have physical and chemical properties very different from the parent substance, but they would probably be produced in such minute quantities as to escape detection by chemical means. The effectiveness of the α rays in producing the phenomena of ionization and fluorescence, and in affecting the photographic plate, by means of which their presence is detected, depends upon the velocity of the α particles. α particles traveling at a velocity only slightly less than that which characterizes the α-ray particles of active substances produce no observable effect. The velocities with which the α particles are emitted is not the same for all active substances, but, on the contrary, each active substance or disintegration product which emits α rays, emits them with a certain definite velocity characteristic of itself. It has been suggested that the "rayless" changes are accompanied by the emission of α particles at velocities below the critical value, which produce no observable effect. The fact that the radio-active substances have the heaviest atomic weights of all known chemical elements lends credence to the idea that their disintegration may be more violent than that of other substances. The suggestion that other substances than those known to be radio-active are undergoing a rayless disintegration accompanied by the expulsion of α particles seems therefore not an unreasonable one.

The age of the Earth has been computed by Lord KELVIN

and others from the rate at which the temperature increases with depth below the surface and on the assumption that the Earth was once a molten mass which has cooled by radiation. The age of the Sun has also been computed on the assumption that it has contracted from a nebula of indefinite extent, transforming the original potential energy of its rarified state into heat and light. The earlier computations led to a maximum age for the Earth and the Sun of something like a hundred million years, and later computations based on data of this sort tend to place the maximum ages at a lower figure. Geological and biological evidences indicate that the Earth must have had a stable crust for several hundred million years. A study of the amount of radium in the soil in many localities and of the radio-activity of the air which penetrates the soil has yielded evidence of the existence of an amount of radium in the Earth's crust sufficient to account for the temperature gradient, observed near the surface, by the heating effect which accompanies its decay. It would seem, then, that the method of calculating the Earth's age from the temperature gradient near the surface is not capable of yielding reliable results. Computations based upon the amount of helium found in a couple of old minerals gave four hundred million years as the age of the minerals.

The age of the Sun depends also upon the amount of energy available for radiation. If we were certain that there is no considerable source of energy supply other than the potential energy of an original diffuse state, as was formerly supposed to be the case, it would be easy to set an upper limit to the period of time during which it can have radiated any considerable amount of heat and light. If, however, the immense stores of energy suspected of existing in the atom are available as sources of heat and light, it would be impossible at present to estimate the life of the Sun either past or future. The existence in the Sun of helium, which is supposed to be a product of the decomposition of radium, makes it seem probable that radium is present also.

The discovery of the existence of electrons having a mass only one thousandth as great as the lightest known atom, and the study of the phenomena of radio-activity have led to theories and speculations regarding the constitution of matter.

Many observed facts indicate that there is an intimate relation between electricity and matter. A portion at least, and possibly all, of the apparent mass of the β particle or electron is due to the charge of negative electricity which it carries. A charge of electricity moving at a high velocity (less than the velocity of light, but of the same order of magnitude) possesses inertia which increases the apparent mass of the charged body. KAUFMANN found that the total mass of the electron might be regarded as due to the charge of electricity.[1] In other words, an electron may be a "disembodied" charge of electricity.

The apparent decomposition of the atoms of radio-active substances and ejection of apparently identical α particles from different elements has tended to strengthen the feeling that has been very general among scientific men for many years, that the atoms are of composite structure, and probably all built up out of some single material. It has been suggested that the electron is the unit of which the atoms are aggregations, characterized by differences in the number and arrangement or motions of the electrons composing them.

One consequence of such an electrical constitution of matter would be a strong presumption in favor of the instability of the atom. Motion of the electrons within the atom implies a certain amount of acceleration of the charged particles, which would result in a radiation of energy and probably in the final disruption of the atom in some way not yet fully worked out.[2]

Another consequence of the theory would be to make matter appear as a form of electricity, and two substances formerly thought of as entirely distinct and different would be found to be but two phases of one substance.

The mass of an electron depends upon the velocity with which it is moving, and any change in its velocity produces a corresponding change in its mass. If the atoms of matter are composed of moving electrons, their mass depends upon the velocity of motion of these electrons, and will be changed by an increase or decrease of their energy of motion. It is not at all unreasonable to suppose, on the other hand, that ordinary forms of energy may pass into that form of energy which con-

[1] *Phys. Zeitschr.* 4, No. 1 b., p. 54 (1902).

[2] Sir OLIVER LODGE, *Nature*, June 11, 1903, p. 128.

stitutes the mass of an atom of matter. Thus the law of the conservation of matter and the law of the conservation of energy would be superseded by a single law of the conservation of matter and energy, it being recognized that matter and energy are but two forms of one thing, just as it is now recognized that heat, which was formerly supposed to be a substance, is in fact a form of energy.

The theories of cosmogony which have been generally accepted up to the present time recognize in the life history of the solar system only a non-periodic process. The continual radiation of heat and light by the Sun is dissipating its original limited store of potential energy, and this supply of energy cannot last at the present rate of expenditure for more than ten or twenty million years longer. At the end of that time, further contraction by the force of gravity being impossible, the Sun is expected to become cold and dark, as the Moon is at the present day. Other suns are supposed to be going through this same process of energy dissipation, so that the whole universe is tending toward a state of uniform distribution of energy and consequent stagnation of all activity. This tendency would not be changed by the occurrence of collisions of celestial bodies, though the conversion of the kinetic energy of their motion into potential energy capable of being transformed into heat and light would prolong the process. Even if through the occurrence of collisions all of the kinetic and potential energy of the universe were made available as heat and light, it would, according to current theories, in the course of time be dissipated and a state of stagnation ensue.

It is assumed also that at the beginning of the process matter existed in a diffuse state, as in the nebulæ, and that at the end of the process it will exist only in a very concentrated state. It is as if the cosmological mechanism were wound up and set in motion to run until it should run down by the dissipation of energy and concentration of matter.

There is something in the human understanding that refuses to accept such a theory as final, and insists that there must be some rejuvenating process supplementing the one just described and making the whole a periodic process repeating itself indefinitely.

If it shall appear that the atoms of ordinary matter are the

storehouses of such comparatively enormous amounts of energy as appear to reside in the atoms of radio-active substances, the total amount of all other forms of energy in the universe will dwindle into insignificance in comparison with the energy of atoms of matter; and if it shall also appear that this energy is capable of being transformed into the radiant energy of heat and light or potential energy, cosmological theory will have to reckon mainly with the transformation of this atomic energy.

Radio-active substances emit the α particles with velocities of something like ten thousand miles per second, which would easily carry the particles beyond the gravitational control of any known mass or system of masses, and amply suffices for the scattering of matter which must form a part of any rejuvenating process that is to complete the cosmological cycle. No theory has been offered to explain the process by means of which the flying particles are recombined into atoms of ordinary matter.[1] That such a transformation should occur under the conditions of tremendous pressure and high temperature obtaining in the interior of a sun would not seem unreasonable; it may be, however, that electric and magnetic forces have more influence upon this transformation than pressure and temperature have. A serious objection to such an hypothesis would appear in the very great amount of energy which would be absorbed in the process, and for which the potential energy of the original diffuse condition of the mass would be totally inadequate.

It would be useless to venture any prediction as to the extent to which the study of the phenomena of radio-activity is destined to modify current theories of the physical and chemical sciences. The questions under investigation are, however, of such vital importance to cosmological theory that this alone is sufficient to command for these researches the intense interest of followers of astronomical science.

LICK OBSERVATORY, November 12, 1906.

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[1] In a note on the "Electric Equilibrium of the Sun" (*Proceedings of the Royal Society of London*, Vol. 73, p. 496), ARRHENIUS concludes that electrons traveling through space with a velocity of the order of magnitude of the velocity of light would be drawn into the stars by the attraction of the charge of positive electricity which there seems reason to believe the latter possess.